Quarterly Report 6 | Covering the Period 15 April to 15 July 1967

OPTICAL TRACKING SYSTEMS

By: E. C. FRASER R. M. DRESSLER

Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
ELECTRONICS RESEARCH CENTER
CAMBRIDGE, MASSACHUSETTS

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INFORMATION AND CONTROL LABORATORY

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ABSTRACT

The work performed from 15 April to 15 July 1967 on Contract NAS 12-59 is described.

In this quarterly report, a conventional autotracker is designed for the earth-based terminal of an optical communication system. The autotrack configuration will be simulated in a digital computer program.

The effort planned for the remainder of the project is outlined.

CONTENTS

ILLUSTRATIONS

I INTRODUCTION

This Quarterly Report summarizes the work performed between 15 April 1967 and 15 July 1967.

The studies that have been completed to date are described in Technical Memoranda 8[1]* and 9[2] and Quarterly Reports 4[3] and 5[4]; these have all been forwarded to the NASA Electronics Research Center. In Quarterly Report 5, optimum linear estimation and control theory has been applied to the design of the earth-based terminal of an optical communication system. A digital computer program has been developed to simulate the operation of the estimator-controller configuration in the system.

In Sec. II of the present report, a conventional autotracker is designed for the earth-based terminal of the optical communication system being studied. The operation of the autotrack configuration will also be simulated in the digital computer program, permitting direct comparison with the performance of the estimator-controller configuration.

The effort planned for the remainder of the project is described in Sec. III.

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*All references are listed at the end of this report.

II AUTOTRACK SYSTEM DESIGN

For purposes of designing an autotrack system configuration for the earth-based terminal of an optical communication link, the block diagram for the declination channel can be drawn as shown in Fig. 1 (the hour-angle channel has identical form).

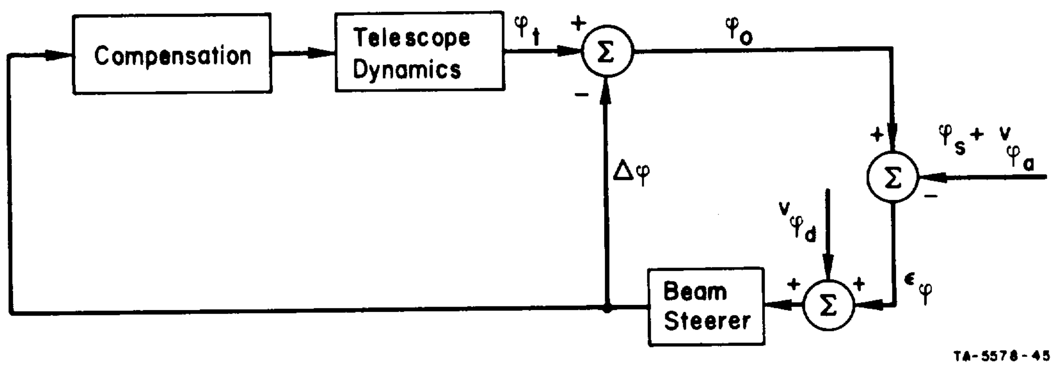

FIG. 1 AUTOTRACK SYSTEM

In Fig. 1, φ_t is the telescope mechanical axis, $\Delta\varphi$ is the offset angle provided by the beam steerer, φ_o is the optical axis, φ_s is the true angle to the spacecraft, v_{φ_a} is the atmospherically induced disturbance, and v_{φ_d} is the measurement noise introduced by the optical detector. The figure can be simplified by noting that the bandwidth of the secondary loop containing the beam steerer is much larger than that of the remaining system; hence its transmission characteristics can be taken as unity. The primary loop of the telescope tracking system then takes the form shown in Fig. 2, where v'_{φ_d} is the measurement noise referred to the beam-steerer output. For the type of system being considered, the measurement noise is expected to be much smaller than the atmospherically induced disturbances; hence the input signal can be approximated by $\varphi_s + v_{\varphi_a}$.

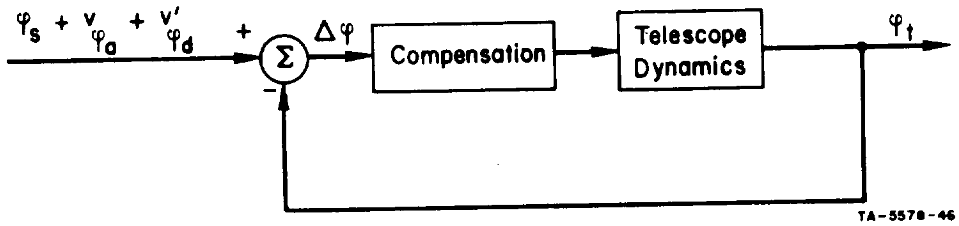

FIG. 2 PRIMARY TRACKING LOOP

The ideal behavior of this system can be defined as the telescope mechanical axis following the true spacecraft direction and ignoring the atmospheric disturbances--i.e., $\varphi_t = \varphi_s$. The design problem thus reduces to the specification of a compensation network, which when used in conjunction with the dynamics of the telescope, will most closely approximate this ideal performance.

A suitable approximation for the telescope dynamics is obtained from the development given in Sec. II-B of Quarterly Report 5.[4] From Eq. (11) of that development, the transfer function for the telescope dynamics can be derived as

$$G_\varphi(s) = \frac{\frac{1}{f_\varphi}}{s\left(\frac{J_\varphi}{f_\varphi} s + 1\right)} \tag{1}$$

for the declination axis, and

$$G_\theta(s) = \frac{\frac{1}{f_\theta}}{s\left(\frac{J_\theta}{f_\theta} s + 1\right)} \tag{2}$$

for the hour-angle axis (J_θ, which varies as a function of φ, is treated as a constant in order to express the above transfer function). Since these two are identical in form, only the declination axis will be treated in detail, and the results simply stated for the hour-angle axis.

As a first approach to the design of a compensation network, we consider the minimization of mean-square tracking error as formulated by Newton, Gould, and Kaiser.[5] Defining the power spectral density of φ_s as $\Phi_{ss}(s)$ and the power spectral density of the atmospheric disturbance as $\Phi_{vv}(s)$, the solution for the optimum compensation network takes the form*

$$G_c(s) = \frac{1}{G_\varphi(s)} \left[\frac{\left\{ \dfrac{\Phi_{ss}(s)}{\Phi^{-}_{\sigma\sigma}(s)} \right\}_+}{\Phi^{+}_{\sigma\sigma}(s) + \left\{ \dfrac{\Phi_{ss}(s)}{\Phi^{-}_{\sigma\sigma}(s)} \right\}_+} \right] \tag{3}$$

where

$$\Phi_{\sigma\sigma}(s) = \Phi_{ss}(s) + \Phi_{vv}(s) \quad . \tag{4}$$

While this optimum compensation does yield maximal separation of the signal and noise power, and does not violate any physical realizability conditions, it has one serious shortcoming that removes it from consideration for use in a practical system. The first factor in Eq. (3), $\frac{1}{G_\varphi(s)}$, is the reciprocal of the telescope dynamics. The effect of this term, when the compensation is cascaded with the telescope, is to completely cancel the telescope dynamics. With the properties of the fixed portion of the system thus removed, the remaining terms of the compensation function then effect the optimum separation of the signal from the noise. Experience dictates, however,

* The specific notation used here is defined in Ref. 2, and since this formula will not be used in this work, the definitions are not repeated here.

that any attempt at "pole cancellation" is doomed to failure since the performance of the resulting system is very sensitive to small parameter changes and will most often become unstable if perfect cancellation is not achieved. Furthermore, if such an approach were attempted, the signal levels required throughout the system would certainly become so large as to violate the fundamental assumption of linearity, and thus invalidate the results.

The above exercise, however, does provide guidance in specifying a simple compensation network. The underlying principle is that if the power in the signal is separated in frequency from the power in the noise, then the frequency response of the system should be modified to respond to the signal but not to the noise. For a typical low satellite (200-mile altitude) the major portion of the signal power will be confined to frequencies below approximately 0.1 Hz; for higher satellites and deep-space probes it will be even lower in frequency.[6] On the other hand, measurements indicate that the atmospheric disturbances have a relatively uniform frequency distribution up to about 13 Hz, and decrease slowly for higher frequencies.[1] Thus, the most desirable approach is to set the system bandwidth near 0.1 Hz so as to ensure adequate signal response and at the same time to eliminate as much of the noise as possible. Therefore, for initial testing the closed-loop system bandwidth has been chosen as 0.1 Hz (0.68 rad/s), which should be adequate for most, if not all, space tracking applications.

The above discussion assumes that load disturbances such as wind gusts need not be considered, since a high-precision telescope would be enclosed within a protective dome. For those cases where load disturbances might be encountered, the closed-loop system bandwidth is to a large extent determined by the requirement that the effect of the disturbance on the system output be minimal. Furthermore, the above argument does not consider the problem of target acquisition. For the very narrow field of view employed during tracking operations, the transient response implied by the closed-loop bandwidth chosen is much too sluggish to permit successful

target acquisition by the tracking system. To accomplish acquisition it will most likely be necessary to increase the receiver field of view and the system bandwidth. These points are discussed in detail in Ref. 1, and need not be pursued further here.

It now remains to design a compensation network that will achieve the desired system performance as described above. A practical approach to this design problem (see, for example, Refs. 5 and 7) is to evaluate the system performance for compensation networks of increasing complexity until the desired behavior is attained. Since the spacecraft angles to be tracked change very slowly for deep-space trajectories and the telescope dynamics contain one integration, it will not be necessary to include a second integration in the compensation network. The resulting Type-1 system will exhibit zero steady-state tracking error for constant inputs, and very small tracking error for ramp inputs.[7]

Trying first a simple gain compensation K_1, as shown in Fig. 3, the closed-loop response is given by

$$G(s) = \frac{1}{1 + \frac{f_\varphi}{K_1} s + \frac{J_\varphi}{K_1} s^2} \quad . \tag{5}$$

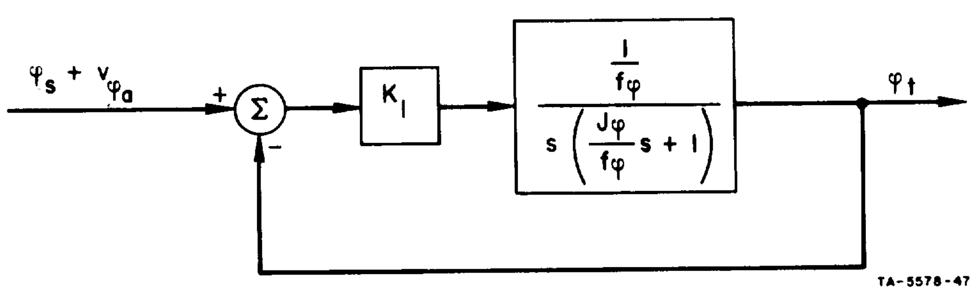

FIG. 3 SYSTEM WITH GAIN COMPENSATION

The bandwidth is therefore

$$\omega_n = \sqrt{\frac{K_1}{J_\varphi}} \quad , \tag{6}$$

and for $\omega_n = 0.628$ rad/s,

$$K_1 = 7.5 \times 10^5 \quad . \tag{7}$$

This value of gain, however, yields a system damping factor of only

$$\xi = 0.0335 \quad . \tag{8}$$

A damping factor this small will result in highly resonant transient behavior, and an amplification of approximately 15 for signals in the vicinity of the resonant frequency; both are undesirable characteristics. To increase the damping, rate feedback from the telescope drive motors can be employed (or, alternatively, a lead-lag network) as shown in Fig. 4,

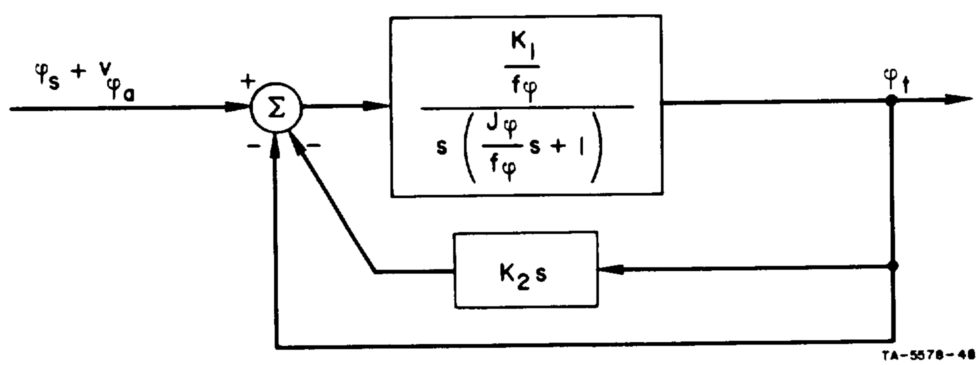

FIG. 4 SYSTEM WITH GAIN COMPENSATION AND RATE FEEDBACK

The resulting closed-loop transfer function is then

$$G(s) = \frac{1}{1 + \left(\frac{f_\varphi}{K_1} + K_2\right) s + \frac{J_\varphi}{K_1} s^2} \tag{9}$$

It is easily seen that the same gain K_1, as in the previous case, will yield the same system bandwidth, and that the damping factor is now given by

$$\xi = 0.314\ (0.107 + K_2) \quad . \tag{10}$$

The value of the damping factor should be chosen to avoid highly oscillatory transient behavior and peaking of the frequency response characteristic. A value of $\xi = 0.7$ provides a transient overshoot of only 5 percent, and the desired closed-loop bandwidth, without peaking. To obtain a closed-loop system damping factor of 0.7 the rate feedback gain is determined to be

$$K_2 = 2.12 \quad . \tag{11}$$

For the hour-angle axis, the only significant difference from the above analysis is the variation of J_θ as a function of φ. Ignoring higher-order and cross-coupling terms -- which is permissible since the rate of variation is very small -- it will be sufficient to consider the system performance for an average value of J_θ, and the performance change as J_θ takes on its extreme values. Taking J_θ to be 1.55×10^6, the forward and feedback gains for a bandwidth of 0.1 Hz and a damping factor of 0.7 are

$$K_1 = 6.1 \times 10^5 \tag{12}$$

$$K_2 = 1.72 \quad .$$

If the system gains are kept at these values and J_θ is varied from a minimum of 0.6×10^6 to a maximum of 2.5×10^6, the system properties change over the range

$$\omega_{n_{min}} = 0.0786\ \text{Hz}\ (0.494\ \text{rad/s}) \tag{13}$$

$$\xi_{min} = 0.55$$

to

$$\omega_{n_{max}} = 0.161 \text{ Hz } (1.01 \text{ rad/s}) \tag{14}$$

$$\xi_{max} = 1.13 \quad .$$

The significance of a damping factor greater than unity is that the system no longer behaves as a resonant system but rather as a pair of cascaded lags, with a resultant effective bandwidth somewhat smaller than that shown in Eq. (14). Since the performance of the system remains within satisfactory bounds over the full range of excursion of J_θ, it is reasonable to use just the one set of fixed gains given in Eq. (12).

It should be noted that the telescope's angular position and rate, which are fed back through the compensation network, will actually be corrupted by measurement noise. This effect will be included in the computer simulation of the autotrack system.

III PROJECTED FUTURE WORK

The effort planned for the remainder of the project is outlined below:

(1) Complete documentation of the computer program according to NASA specifications.

(2) Investigations with the program to evaluate the performance of the estimator-controller configuration under varying conditions of measurement noise for different spacecraft trajectories. This entails final "tuning" of the estimator and controller.

(3) Studies to determine the sensitivity of system performance to model inaccuracies.

(4) Studies to evaluate the degradation in system performance as the increment time Δt is increased. This is an important consideration for real-time applications, since the computation time is directly related to Δt.

(5) Simulation in the computer program that has been developed of the autotracker designed in Sec. II. This will enable direct comparison of the performance of the estimator-controller configuration.

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